JERUSALEM ISRAEL
1 9 9 4

IAF -94-().3.339

# LOW COST APPROACH TO MARS PATHFINDER


Anthony J. Spear
Mars Pathfinder Project Manager
"Mars Pathfinder Project
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California



**45th** CONGRESS OF THE
**INTERNATIONAL** ASTRONAUTICAL FEDERATION
October 9-14, 1994 /Jerusalem, Israel

IAF-94-Q.3.339

# LOW COST APPROACH TO MARS PATHFINDER[1]

Anthony J. Spear
Mars Pathfinder Project Manager
Mars Pathfinder Project
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

## Abstract

Mars Pathfinder, launching in December '96 and landing in July '97, will demo a low cost delivery system to the surface of Mars. Historically, spacecraft that orbit or land on a distant body carry a large amount of fuel for braking. Mars Pathfinder, thrusting only for navigation, enters directly into the Martian atmosphere, aerobrakes with its aeroshell, deploys a parachute at 10 km above the surface and, within 100 m off the surface, ignites solid rockets for final braking prior to deployment of air bags which cushion touchdown. After landing, petals open to upright the lander, exposing solar panels to the sun.

Even though the lander and rover are expected to last longer, the major objectives of Mars Pathfinder, demonstrating EDL (Entry, Descent, Landing) and lander-rover surface operations, will occur within the first few days, at which time panoramic images of the surface will be transmitted and the rover will be deployed to conduct both mobility tests and rock composition measurements.

While Mars Pathfinder is primarily an engineering demo, it accomplishes a focused, exciting set of science investigations with a stereo, multi-color lander imager; atmospheric instrumentation, used as a weather station after landing; and the rover with cameras and the APX (Alpha Proton X-ray Spectrometer).

This paper features Mars Pathfinder's approach to innovative and cost effective mission accomplishment, under a development cost cap. Mars Pathfinder is pathfinding a new way of doing business at NASA and JPL for small, low cost, Discovery class missions.

## Mars Pathfinder Concept

Pathfinder represents a different approach to a Mars lander mission, signaling NASA's transition to low cost, fast track missions. Past missions launched massive spacecraft combinations of landers and orbiters on large launch vehicles. Viking orbiters carried landers into orbit prior to release for landing, while Russian spacecraft released their landers prior to arrival. All past landers relied on orbiter relay links as the primary communications path and used RTG's (Radioisotope Thermoelectric Generators) for power.

With a smaller launch mass, Pathfinder launches from a medium size, Delta II launch vehicle, totally self contained: flying on its own to Mars, and using a direct link to Earth. Instead of a RTG, the Pathfinder lander is powered by solar panels and battery.

A centralized system architecture, built around a radiation hardened, commercial, 32 bit computer, controls cruise, EDL and surface operations.

Communication equipment, housed in the lander provides up and downlink with Earth in cruise and during surface operations. A downlink is established with Earth to the extent


Mars Pathfinder Project Manager

[1] The work described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

possible during EDL. Using a cruise direct entry approach pioneered by NASA's Ames Research Center, Mars Pathfinder carries enough propellant for trimming the flight path only. A cruise deck, with navigation thrusters, propellant, star and sun sensors, thermal control and a medium gain antenna is ejected from the capsule containing the lander 24 hours before EDL.

On the surface, the rover, supported by the lander's multi-color, stereo camera, provides access to rocks, and with its close up cameras and the APX, the potential for reading the history of Mars' geological processes. What started out as an engineering mission primarily, has turned into a potentially exciting scientific investigation. With this in mind the project, supported by its PSG (Project Science Working Group), selected a "grab bag" landing site, 19 Deg. North latitude, 32.8 Deg. West longitude at Chryse Planitia, one that not only satisfied engineering constraints (low elevation, under the sun, low wind, rocks less than 0.5 m) but which is situated at the confluence of two water channels, with evidence of catastrophic flow, which may have brought down a variety of rocks from the highlands.

## Mars Pathfinder Challenge

Pathfinder was initiated in '92, subject to the following groundrules:

- Demo a low cost delivery approach to the Mars surface at the '96 opportunity
- Carry and deploy a microrover
- Accomplish both development and operations under relatively low cost caps
- Establish a new way of doing business for low cost, fast track deep space, robotic missions

The project, faced two major challenges: technical and programmatic. In addition to the normal mission and engineering tasks associated with implementing a space mission, it had to find a way to do it quicker and cheaper, providing more product for each $.

For the first challenge, the following technical trades were made:

- Cruise-EDL-Lander system architecture
- EDL approach
- Relay link vs direct link communications
- Battery only vs solar power and battery for the lander power source
- Tethered vs untethered rover

We quickly adopted the Ames direct entry approach to avoid the need of carrying a large supply of fuel to the planet for braking, aerobraking in the atmosphere instead. Our entry velocity is 7.6 km/sec, compared with 4.6 km/sec for Viking landers, significantly higher, but within design limits. Ames has conducted arcjet testing of the Viking SLA-561 ablator material to show that a Viking derivative aeroshell using this ablator material can be used for Pathfinder's direct entry approach.

The next step dealt with designing a cost effective flight system architecture to carry the lander to Mars. One approach studied was the design of a separate cruise spacecraft to carry the lander to Mars. The lander, housed inside the EDL capsule, would be attached to the cruise spacecraft and released for EDL at the proper time. To reduce equipment and cost, the decision was made instead to build an integrated flight system around a central computer which conducted cruise, EDL and surface operations functions.

This approach is made possible with the use of a powerful, flight computer which accomplishes the following functions:

- Fault detection and safing
- Lander and rover command and telemetry
- Cruise attitude control and maneuvers
- EDL sequencing control
- Science data processing
- Lander image compression

For EDL, we studied both active vs passive approaches, ie a Viking like, 3 axis control, rocket deceleration vs a Russian like, semi hard impact using air bags and uprighting petals. We interacted with all available areas of expertise in this technology including NASA's Ames and Langley Research Centers, Sandia National Labs, industry, ESA and Russia.

After much deliberation in an August '92 peer review, we selected the following EDL approach:

- Viking derivative aeroshell
- Viking derivative disk-gap-band parachute
- DOD (Department of Defense) derivative small solid rockets
- Russian/auto industry like air bags

• Russian like uprighting petals

In the Pathfinder trade study, no EDL approach was singled out as the ultimate. Each has its set of advantages and disadvantages. The Pathfinder approach, robust, promising low recurring cost and adaptable to a large set of missions, is a unique compilation of subsystems with significant design heritage, except that the space qualification of air bags represents a significant development. It is affordable under the cost cap and represents the culmination of a thorough, but not exhaustive trade study that had to end quickly to maintain the fast track schedule.

Landing site accuracy is on the order of 200 km x 100 km 3 sigma - good for deployment of geoscience, meteorology and seismic stations.

More accurate landings, say for delivery to a base, will require a 3-axis, retro-propulsive approach, possibly with homing devices and hazard avoidance. Mars sample return landers may adjust their final approach, not on why to avoid hazards, but to actively seek out a more desirable landing site to accomplish its mission.

Under the cost caps, an orbiter in support of the Mars Pathfinder lander was clearly not affordable. The decision was made to build into Pathfinder a significant direct link capability so that it could stand alone, not be reliant on orbiters that may be at Mars for relay communications.

The expense and time associated with the implementation of a RTG was judged not compatible with Mars Pathfinder's low cost, 3 year development approach. Instead, battery only and solar panels/battery approaches were studied as lander power options. The solar panel with battery approach was selected primarily for the following two reasons:

• a battery only option could not guarantee sufficient lander surface ops lifetime for support of the rover
• in the spirit of Pathfinder's engineering mission, demonstrating solar panel performance on the surface of Mars was deemed an important engineering objective

NASA's Lewis Research Center provides support on solar panel performance in the Martian surface environment.

In the course of implementing both the lander direct link and the solar panel power source, we have realized the following lander system architecture lessons and technology needs:

Lessons

• the use of a significant lander direct link, powered by solar panels, establishes a limit on lander miniaturization -- no matter how small the payload can be made, solar panel area will dictate lander size.
• very small landers, exploiting emerging microelectronics, can be achieved using an orbiter relay link communications approach. The flight of Mars Surveyor small orbiters will provide this opportunity.

Technology Needs

• store and dump techniques for low power communication links with large transmitter antenna aperture, possibly at Ka Band
• efficient, solid state transmitters up to Ka Band
• efficient, lower mass and volume, chargeable batteries

We studied both tethered and un-tethered rover approaches. Tethered, the rover would remain connected to the lander through a wire and would rely on the lander for power and computer processing, and the need for a lander-rover RF link is eliminated. However, a tether restricts rover mobility and would require a more interactive rover-lander development. In the spirit to push to do more for less, a decision was reached to implement a fully autonomous, non-tetherd rover. The rover is self-powered using a solar panel and a primary battery, has its own computer for data processing and surface navigation and communicates with the lander over a 11111; link, adapting a commercial modem for space use. It employs a 6 wheel "rocker-boogie" mobility approach which provides for a steady platform while navigating a rocky surface. If the rover was the size of an automobile, then the rover would be able to move over objects the size of a dining room table.

NASA's Office of Space Science is developing Pathfinder. The Advanced Concepts and Technology Office teamed with the Space Science office is developing the Pathfinder rover.

Pathfinder is being performed at JPL in its in-house, subsystem mode.

Mars Pathfinder Implementation Strategy

For its second challenge, a new way of doing business, Pathfinder implemented a special "cheaper, better, faster" project operating mode, using a "Kelly Johnson" like skunkworks approach, focusing on a limited set of objectives, and streamlining project approaches and minimizing bureaucratic interference.

To land on Mars with a rover at low cost, the Pathfinder project:

- Acquired institutional support priority within JPL, in particular, in quick formation of a motivated, projectized, collocated "skunkworks" team
- Achieved IJ@/rent Agreements with JPL and NASA management, which are documented in the Pathfinder Project Plan and must be maintained
- Acquired support in key EDL technologies from Sandia National Laboratory and NASA's Langley and Ames Research Centers and industry
- Leveraged NASA's investment in JPL's planetary mission infrastructure, making cost effective use of mission design tools, navigation techniques, multi-mission GDS (Ground Data System) and MOS (Mission operations System) capabilities, and the JPL Flight System Test Bed
- Balanced use of available and new technology, each application weighed carefully as to its contribution to low cost, performance, and lower risk
- Supported NASA in streamlining the lander camera AO (Announcement of Opportunity) process which led to selection of a powerful camera utilizing the Cassini Huygens Probe CCD (Charge-Coupled Device & Electronics) and its associated electronics
- Practiced concurrent engineering from the outset among mission, navigation, flight system, instruments, rover, ground data system, ops, product assurance, procurement
- Accomplished early proof of concept testing for EDL, and the rover
- Is performing early interface/functional testing in the JPL Test Bed among the flight system, instruments, rover, flight S/W (Soft ware), GDS, MOS sequences
- Will assembly quickly and test thoroughly. ATLO (Assembly, Test, Launch Operations) begins 18 months before launch

Pathfinder was funded sufficiently in its 19 month pre-project phase to get a jump start on development, performing the aforementioned technical trades; completing significant flight system, rover instruments, GDS and MOS design; and performing detailed planning and cost estimating. Its design, implementation and cost estimates were reviewed formally twice in the pre-project phase by a Standing Review Board -- the July '93 pre-project review being its System PDR (Preliminary Design Review) and NAR (Non-Advocate Review) equivalent.

At project start in October '93, we had a significant segment of the GDS up and running, had performed an Earth-Lander-Rover uplink/downlink data test and was ready with long lead procurement documents. Three months after project start, an Integrated Project Schedule and a cost update were completed. The Integrated Project schedule details all key steps necessary across all project elements for launch on December 5, '96, including both Pasadena and ETR (Eastern Test Range) ATLO.

The cost update reflected changes in the plan due to the loss of Mars Observer spares.

With all major procurements initiated, the baseline Pathfinder development scope is costed at 146 Mil $, and we currently hold 25 Mil $ reserves, adding to 171 Mil real year $, equivalent to the 150 Mil $ (FY '9?) cap. Exploiting the JPL existing multimission institutional infrastructure has permitted acquisition of the GDS and MOS for 12 Mil $, a substantial reduction to that which has been spent historically at JPL. The total allocation for science and instruments is 15 Mil $. The APX, developed for the. Russian Mars '94 mission, costs 1.0 Mil $ plus another 1.0 Mil $ for the APX deployment mechanism. The lander camera is being furnished by the PI (Principal Investigator), cost capped at 5.0 Mil $. Project management is costing 5 Mil $. The largest use of funding at 114 Mil $ is directed at flight system development.

The rover is being developed for 2.5 Mil $ real year, in addition to the 171 Mil $ Pathfinder development allocation.

Because Pathfinder is probing to do more for less, the following development priorities were established, keyed to mission success crit eria, and wi 11 guide the use of reserves and dc.scope decisions, if necessary, to stay within the Cost cap:

Pathfinder 1 level.o]~lllc]lf. j'lioljtics

1. Delivery System to Mars: cruise and 1 ΣDL
2. Cruise and EDL telemetry instrumentation for realtime and stored telemetry transmission
   a. cruise, cruise separation and 10)1. critical event telemetry
   b. g levels in atmosphere and on landing
   c. aeroshel I temperat urc/pressure measurements
3. Transmission of stored 1 EDL and realtime lander engineering telemetry as soon as possible after landing
   - 50% mission success -
4. Transmission of a subset of the panoramic image
   - 70% mission success -
5. Deployment of the Rover and support of Rover engineering operations
   - 90% mission success -
6. Transmission of APX data with APX deployed against rock and soil by Rover
7. Transmission of camera science data acquired in daytime, dawn to dusk, for 7 (lays
8. Transmission of camera science data acquired in nighttime for'? days
9. Transmission of stored atmospheric science (accelerometer, pressure, temperature) data after landing
10. Transmission of surface measurements of temperature and pressure for 30 days
11. Transmission of camera science data acquired in daytime, dawn to dusk, for 30 days
12. Transmission of camera science data in nighttime for 30 days
   - 100% mission success -

The most important feature of Pathfinder's approach is col locat ion of key team members on the same floor of one building around the JPL Flight System Test Bed. Collocation simplifies lines of communication and facilities rapid iteration of requirements and resolution of issues and problems. Team members from the JPL technical divisions remain administratively tied to their home division, in what is called tbc "soft projectized mode", but are responsible to the project for performance, cost and schedule of their work packages, not to the divisions. Wc arc self-containc(i, including product assurance anti procurement teams collocated with the project.

Oar Project Engineering Team (PET), with membership from all project elements, is our major concurrent engineering vehicle. PET coordinated Project document development including tbc Project Plan and lower level requirements stemming from the Project Plan's Level 1 requirements. PET is responsible for tracking compliance to requirements, for planning increment al H/W (Hard ware) and S/W deliveries to the JPL Test Bed for early phased testing, as capabi li ties evolve, and for coordinat ing the Engineering configuration Control and Problem/Failure processes. PET also acts as the project referee in working "PET PEEVES": problems that impact requirements or have an impact to other elements of the project. The early phased tests in the J]'], Test Bed essentially gives us a head start on A"]'10 with car] y int erface and functional testing in parallel with developments, prior to the formal start of ATLO in June '95.

Pathfinder is being fabricated, assembled and tested at JPL. Major contracts have been initiated for the flight computer, aeroshell, parachute and air bags.

Pathfinder uses the following available equipment or designs:

- Cassini transponder
- Magellan Star Scanner
- Adcol Sun Sensors
- Viking heritage aeroshell and parachute designs
- DOD developed RAD rocket s and altimeter

All flight equipment is being subjected to rigorous inheritance review and space qualification testing tailored to the Pathfinder mission regardless of previous testing history.

Pathfinder's key new technology uses include:

- A free ranging rover with on-board autonomous navigation
- Rover thermal enclosure
- A solid state X-Band power amplifier
- A RAD hardened, commercial flight computer
- Air bags adapted for use at Mars
- Lander image data compression

The rover, X-Band and power amplifier and EDL, in particular the air bags represent the major developments, and significant work was accomplished on each of these in the pre-project phase including proof of concept air bag tests at Sandia, rover mobility tests and breadboard power amplifier development at JPL.

For the EDL, comprised of subsystems with heritage (air hags the exception), the challenge lies with incorporating these subsystems into an effective, space qualified system. EDL system demonstration and space qualification testing arc of major importance, but they are not on the critical path relative to ATLO and can be accomplished largely independently, in parallel with ATLO.

ATLO critical path items include the lander structure, harness, PC) WC] subsystem, AIM (Attitude & Information Management subsystem embodying the flight computer), the flight S/W and the rover.

We have planned ATLO at one shift per day, S days per week in Pasadena, and 6 days per Week at ETR. We hold 22 weeks of schedule margin distributed in ATLO, in addition to extra shifts and weekends, the support cost of which is bookkept as a lien on reserves.

Pathfinder' S major programmatic challenge is:

- Accomplishment of both the Pathfinder and rover developments within their cost caps: ]'11 and 25 Mil $, real year, respectively.

Accomplishing development in 3 years is a lesser challenge, especially with the quick start made possible by the pre-project phase.

Except in FY '93 where there arc two, Pathfinder conducts one formal review each year before a Standing Review Board with the System CDR (Critical Design Review) in September '94 the next review. An ATLO Readiness Review conducted in May '95 and a pre-ship, MOS Readiness Review conducted in August '96 arc the remaining formal reviews before launch. In May '97, a Surface Ops Readiness Review will be conducted.

Mars Pathfinder Key Milestones

| | |
|---|---|
| Project Start | 10/1/93 |
| System Critical Design Review | 9/94 |
| ATLO Readiness Review | 5/95 |
| ATLO Start | 6/95 |
| Launch Readiness Review | 8/96 |
| Launch period | 12/5/96 - 1/3/97 |
| Surface 01'S Readiness Review | 5/97 |
| Landing on Mars | 7/4/97 |
| Complete 30 day surface mission | 8/97 |
| End of Mission | 8/88 |
| End of Project | 9/98 |

Mars is most Earth-like of the terrestrial planets and may have supported life. It has stirred interest and imagination for many decades and will continue to be the target for human exploration in the next century. A no less important objective is communication to the public of Pathfinder's exciting robotic exploration of Mars, including student interaction with the mission through Pathfinder's Education Outreach program. in addition, Pathfinder's Technology Transfer Plan identifies technologies with commercial spin-off potential.

## Mars Pathfinder Mission Description

A single Mars Pathfinder flight system will be launched to Mars in the period December 4, 1996 to January 3, 1997 from a Delta 11, landing on July 4, 1997. The flight system is spin stabilized during cruise, spinning at 2 rpm, with the spin axis and medium gain antenna pointed to earth except for the first few days after launch, when the spin axis may be pointed closer to the sun line. After the first 20 days, the sun line remains within 40 degrees of Earth, and the earth point attitude is maintained until Mars atmosphere entry, including cruise trajectory maneuvers which are performed in a vector mode: thrusting along or perpendicular to the spin axis. All cruise critical events are telemetered in real time to earth.

Twenty four hours before Mars arrival, the flight system, keeping in touch with Earth, will jettison its cruise stage and enter directly into the Mars atmosphere, braking with an aeroshell, parachute, small solid retrorockets and air bags.

The entry velocity is 7.6 km/sec ( 17,100 mph) compared with Viking at 4,6 km/sec which entered from orbit. Mars Pathfinder's entry angle is 16.7 deg. (90 deg. would be straight down) and peak atmospheric shock, 25 g's, is encountered at 32 km above the surface. The parachute is deployed at Mach 1.8 (900 mph) at 10 km, 100 seconds after atmospheric entry.

EDL engineering telemetry will be transmitted to Earth in real time to the extent possible. Before chute deployment, earth remains near the spin axis behind the craft and communication to earth is through a low gain antenna at 40 bps. After chute deployment, the Earth moves to approximately 90 deg. from the spin axis including chute swing, making communications more difficult. At this time, we will accomplish carrier presence detection only. " EDL, lasting for 5 minutes, will be supported with the 70 m most likely arrayed with available 34 m antennas. Pathfinder lands semi hard at up to 20 m/s horizonal and up to 20 m/s vertical velocities. Landing will be limited to <50 g's using an air bag system designed to accommodate 1/2 m size rocks. The lander tumbles and rolls across the surface and rights itself using petals much like an opening flower. After opening, the petals expose solar panels to the Sun for powering surface operations.

After landing, the lander will transmit stool EDL data and real time lander and rover engineering telemetry first. Panoramic images of the surface will be also transmitted to Earth the first day. 'The. rover will be deployed as early, as the first day, for start of its surface operations. The rover conducts surface mobility experiments, images rocks and soil and deploys the APX on soil and against rocks. While 30 day and 7 day primary surface missions are planned for the lander and rover, respectively, close to 100% of all lander and rover engine.cring and science objectives are achieved nominally in the first few days of surface operations. Currently, no life constraint precludes operations of the lander or the rover past their primary mission requirements.

The Pathfinder scientific payload includes instrumentation for measuring atmospheric and landing deceleration; pressure and temperature during entry and while on the surface; a 12 spectral channel, stereo lander camera for surface and atmospheric imaging, including imaging magnetic properties targets, a wind sock and support Of rover navigation; and the rover-deployed APX for elemental composition measurements of rocks and soil. The rover carries aft and forward cameras for demonstrating autonomous hazard avoidance and imaging its local surroundings, soil and rocks, and the lander.

## Mars Pathfinder Major Contributions to Future Landers

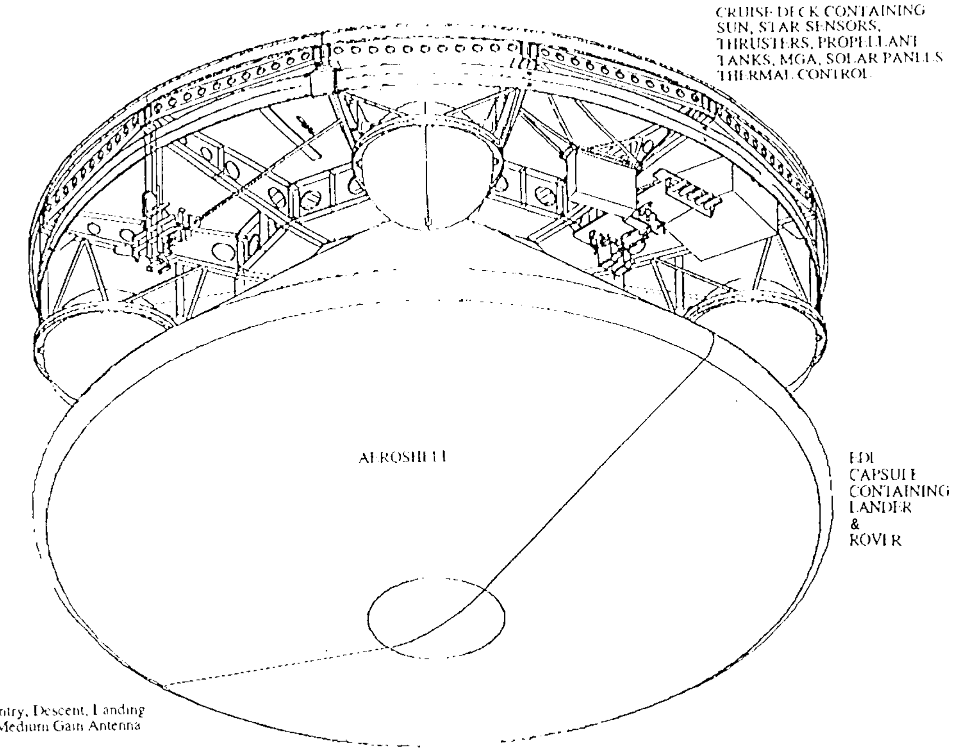
The combination of Pathfinder's development and operations experience base with that acquired by Viking will provide an extensive, demonstrated set of U.S. capabilities for future Mars landers.

Future landers may be launched to Mars as early as '98 in the Mars Surveyor or Discovery Programs. Some of these landers will be close derivatives or smaller versions of Pathfinder. In addition, further study of small lander architecture is underway in support of the. Mars Surveyor Lander Program. One Discovery proposal is planning to land a near Pathfinder duplicate vehicle at North Pole of Mars. Other landers will repackage Pathfinder's centralized system architecture using emerging micro electronics and lighter materials to reduce size and volume. This will have a ripple effect in reducing end to end mission cost, in particular in enabling launches of landers from smaller launch vehicles. These smaller landers will have. a focused science investigation objective, around one or a few measurements, determined by the NASA AO process.

Mars Pathfinder major contributions to future landers are designs, developments, lessons learned, in particular:

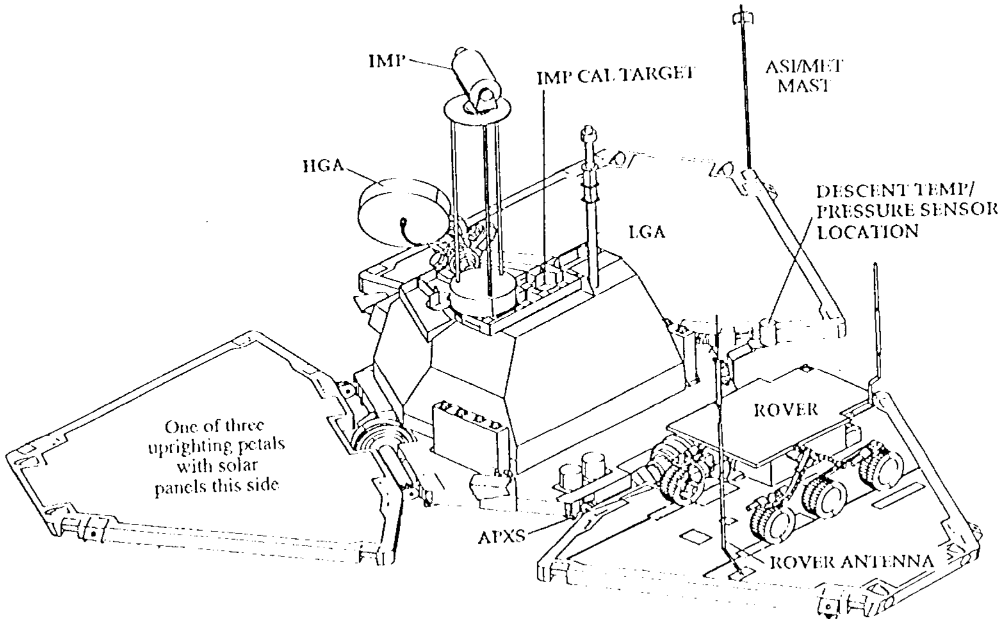
- A low cost, fast track project approach
- A low cost, robust, entry, descent, landing system scalable to other missions
    - Aeroshell, parachute, RAD, air bags, uprighting petals can be individually or wholly used by follow-m missions
- A self-contained flight system architecture
    - Can fly to Mars on its own
    - Can communicate directly with earth
- A stereo, multi-color surface imager
- A free ranging, autonomous navigating rover with instrument placement capability
- Solar powered lander and rover

* The carrier will be amplitude modulated at this time to communicate critical events only such as aeroshell, and chute deployments, RAD firing and air bag deployment.




EDL = Entry, Descent, Landing
MGA = Medium Gain Antenna

MARS PATHFINDER CRUISE CONFIGURATION




IMP = Imager for Mars Pathfinder
HGA = High Gain Antenna
LGA = Low Gain Antenna
APXS = Alpha Proton X-ray Spectrometer
ASI/MET = Atmosphere Structure Instrument/Meteorology

MARS PATHFINDER LANDER & ROVER